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INTO A BAFFLED SPHERICAL TANK  
DURING WEIGHTLESSNESS**

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*Cleveland, Ohio*

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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# AN EXPERIMENTAL STUDY OF LIQUID FLOW INTO A BAFFLED SPHERICAL TANK DURING WEIGHTLESSNESS

by Charles R. Andracchio and Kaleel L. Abdalla

Lewis Research Center

## SUMMARY

An initial investigation of liquid flow into a baffled spherical tank during weightlessness was conducted. A sphere within a sphere configuration was tested using a partially wetting liquid and a totally wetting liquid while varying the percent initial filling in the tank.

Both liquids can be pumped into the tank over a range of velocities which maintain the liquid-vapor interface in a stable orientation; the maximum value of these velocities is a function of initial liquid filling in the tank. A baffled tank allowed higher stable filling rates than an unbaffled tank; similarly, the partially wetting liquid allowed higher stable filling rates than the totally wetting liquid. The use of a deflector mounted on the baffle improved the stable filling rate of the totally wetting liquid at low initial fillings.

## INTRODUCTION

During future long-termed spaceflights it will become necessary to transfer liquids from one container to another in a weightless environment. As an example, it has been proposed that an in-orbit propellant transfer be employed to resupply fuel to orbiting space vehicles or spacecrafts. In regenerative life-support systems, potable water, after being separated from its vapor, will have to be collected and stored and be ready for distribution to the crew members; similarly, waste water will be collected and transferred to heat exchangers for processing. Other applications of liquid transfer can be found in fuel cells and on individual spacesuit backpacks when crew members must function in space outside the cabin's controlled atmosphere. The size and shape of the transfer containers, as well as the properties of the liquids, are important considerations in the design of the transfer system. Therefore, an investigation into the problems associated with in-orbit fluid transfer seems in order at this time.

Transferring fluids from one container to another in zero gravity presents problems concerning the disturbance of the liquid-vapor interface in both the supply and the receiver tanks. For example, during the outflow of liquid from a cylindrical container in a weightless environment, it has been established that interface distortion or vapor ingestion will occur before the container has been completely drained (refs. 1 and 2). Nussle, Derdul, and Petrash (ref. 1) have found that interface distortion can be minimized and vapor ingestion can be delayed by diffusing the incoming pressurant gas and baffling the tank outlet. In reference 2, a correlation of interface distortion with Weber number has been obtained using initial filling as a parameter. At any rate, outflow studies have been in progress and the interface distortion and vapor ingestion problems seem to be essentially resolved.

On the other hand, the behavior of fluids being pumped into containers in zero gravity has not yet been experimentally investigated. Basic questions arise as to what rate can be used to transfer liquid to a tank without violently distorting the liquid-vapor interface. The incoming kinetic energy of the liquid might have to be dissipated; otherwise, the impacting liquid on the tank might cause damaging stress loads. Geysering might occur, or the incoming liquid might position itself over the tank's venting port. Conversely, inherent surface tension characteristics could be advantageously used to allow the liquid to be transferred to the receiver tank in a controllable or stable manner.

Baffled tanks should have an effect on pumping rate whether the baffles are formed mechanically or by the liquid itself. Surface tension baffles, such as the standpipe and the sphere within a sphere configurations, have been investigated by Petrash and Otto (refs. 3 and 4) and were proven to be an effective means of stabilizing the static liquid-vapor interface in zero gravity. Nevertheless, the effectiveness of these baffles under flow conditions must yet be determined.

The purpose of this report is to present the results of an initial study regarding inflow characteristics of a baffled spherical receiver tank while being filled during weightlessness. A sphere within a sphere tank geometry was chosen for investigation because this type of tank configuration can control the location of the liquid-vapor interface over a wide range of fillings (ref. 5). The inner spherical baffle diameter was 60 percent of the tank diameter, which allowed a filling of 90 percent of the total tank volume, and assured stabilization of the ullage bubble over the vent. For comparative purposes, some tests were made with unbaffled tanks. No attempts were made to obtain a scaling parameter; however, two liquids were tested, water and ethanol, to determine what effect a partially wetting and a totally wetting liquid had on inflow characteristics. The tests were performed in the NASA Lewis Drop Tower allowing 2.3 seconds of weightlessness.



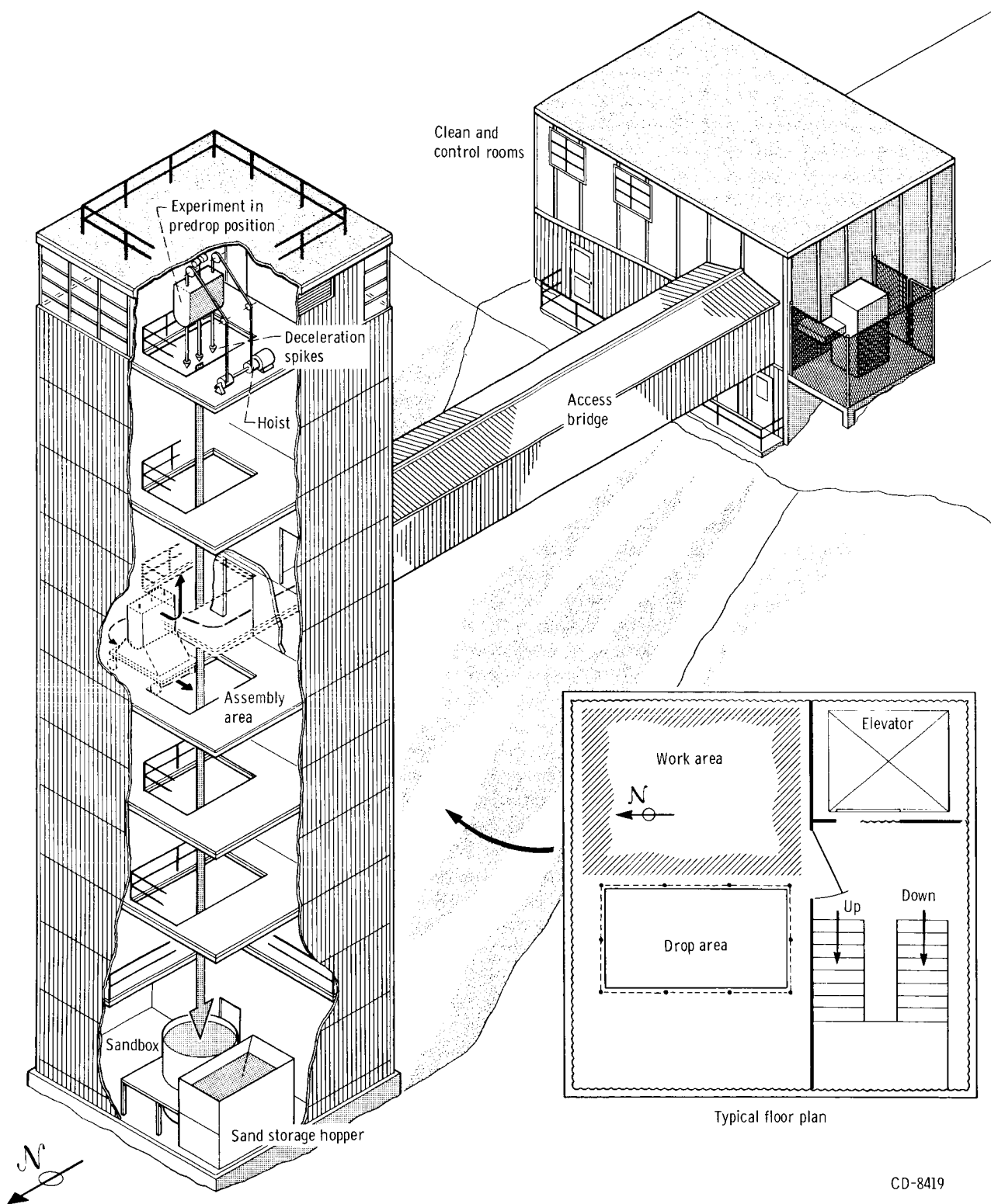


Figure 1. - View showing 2.3-second drop tower.

# APPARATUS AND PROCEDURE

## Test Facility

The experimental tests were performed in the Lewis Research Center's 2.3-second drop tower shown in figure 1. Approximately 2.3 seconds of weightlessness were obtained by using the maximum free-fall distance of 26 meters. Air drag was minimized by the use of a drag shield. The experiment package was installed into the drag shield and hoisted to the predrop position; both drag shield and package were suspended with a wire and then released simultaneously. Thus, the package fell relative to the falling drag shield, and the effect of air drag on the experiment was less than  $10^{-5}$  g's. Figure 2 shows the various positions of the experiment package and drag shield during a test drop. A detailed description of the drop facility is given in reference 6.

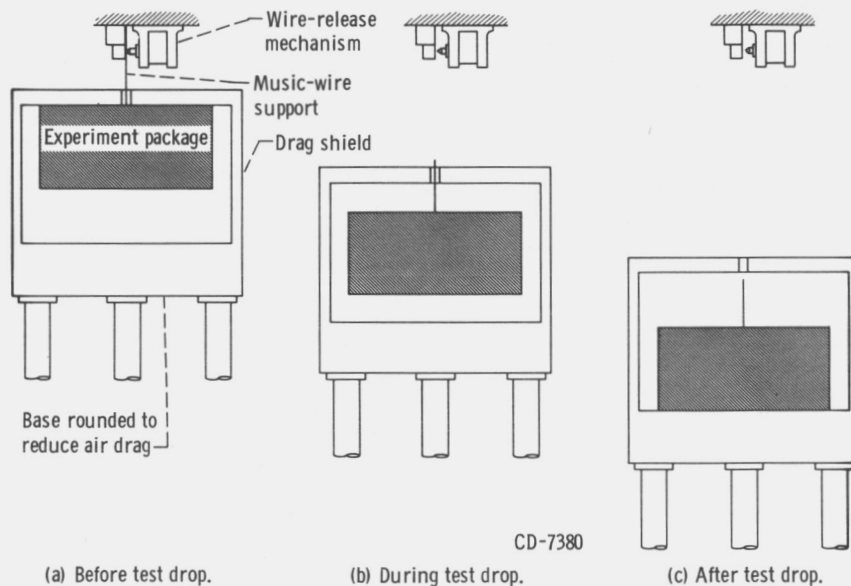
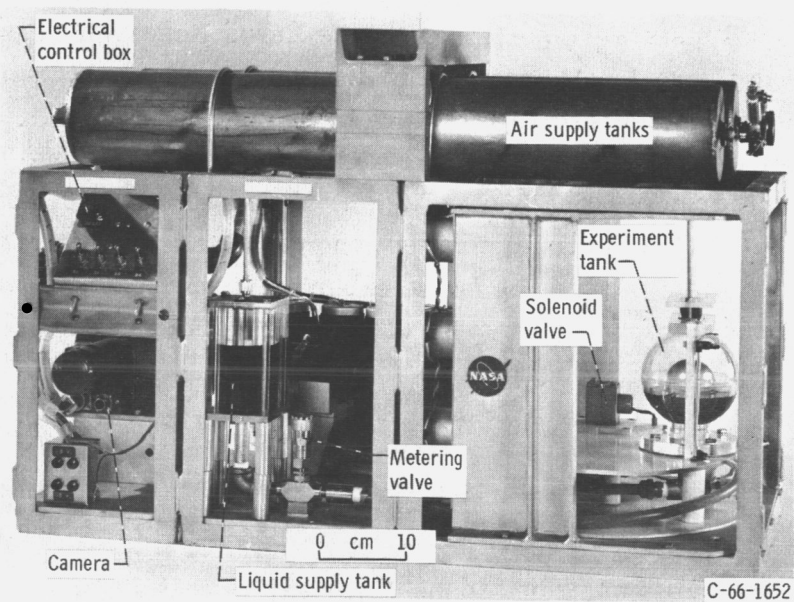


Figure 2. - Schematic drawing showing position of experiment package and drag shield before, during, and after test drop.

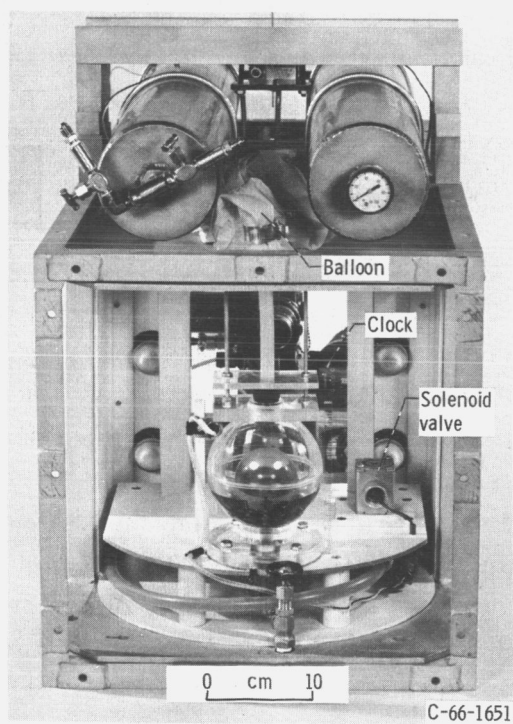
## Experiment Package

The experiment package, as shown in the photographs of figure 3, is essentially an aluminum framework which houses the experiment tank and the photographic, pumping, and electrical systems.

The experiment tank consisted of a 10-centimeter-diameter hollow sphere, which contained a 6-centimeter-diameter solid spherical baffle as shown in figure 4. The smaller sphere was offset from the tank's centerline a distance of 1 centimeter toward



(a) View showing supply tank and components.



(b) View showing experiment and components.

Figure 3. - Experiment package.

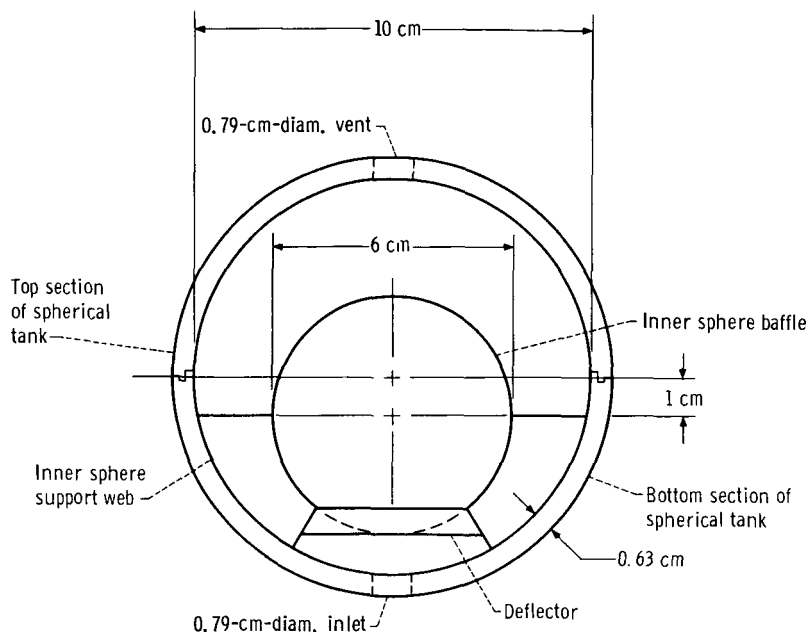
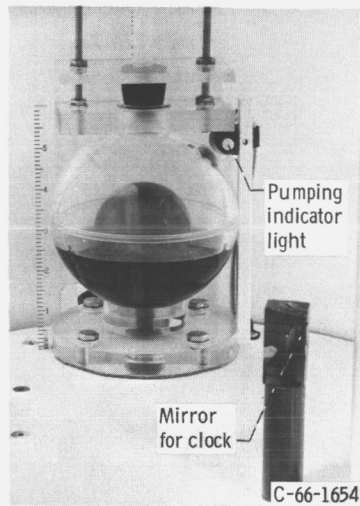


Figure 4. - Tank dimensional sketch.

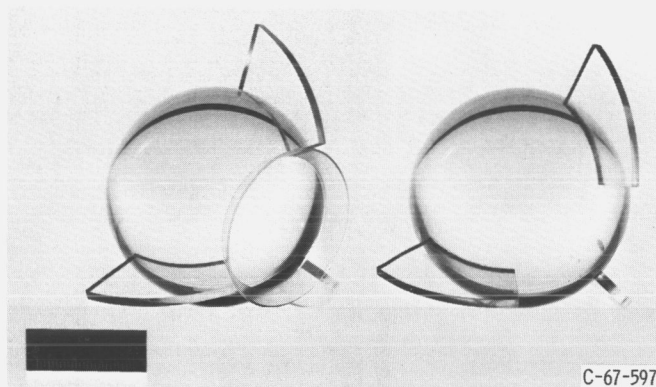
the tank's inlet. The baffle was glued to the lower half of the tank using three equally spaced webs as supports. During some of the tests, a deflector was fastened to the baffle to redirect the incoming liquid toward the tank walls. The tank, baffle, deflector, and webs were made of annealed, cast-acrylic plastic; the tank and baffle were highly polished to improve photography. Figure 5 shows the experiment tank mounted in the experiment package and also the baffle with and without the deflector fastened to it.

The photographic system contained a camera, a clock, and a lighting arrangement. A high-speed camera was operated at approximately 500 frames per second. Indirect lighting was used in a light box to illuminate the experiment tank. A digital clock measured time accurate to 0.01 second.

The pumping system consisted of supply tanks, metering and solenoid valves, the experiment tank, and the associated liquid-transfer lines. A schematic diagram of the pumping system is shown in figure 6. The air supply tank provided pressure to the liquid supply tank. The pressurized liquid was then transferred through a metering valve and a shutoff solenoid valve to the experiment tank. The liquid supply tank was an 8-centimeter-inside-diameter plastic cylinder 12 centimeters long. Baffles were mounted over the inlet and outlet of the supply tank. A weather-type balloon was installed at the experiment tank's vent as a collection device for any escaping liquid. Back pressure from the balloon was negligible because of its large total volume with respect to the volume of air entering it. The electrical system was composed of a 45-volt battery power supply and a control box containing switches, relays, and timing units. Thus, the control box enabled power to be supplied to the photographic and pumping systems at the prescribed time during the sequence of events.



(a) View of experiment tank positioned in experiment package.



(b) View of baffle showing deflector.

Figure 5. - Experiment tank.

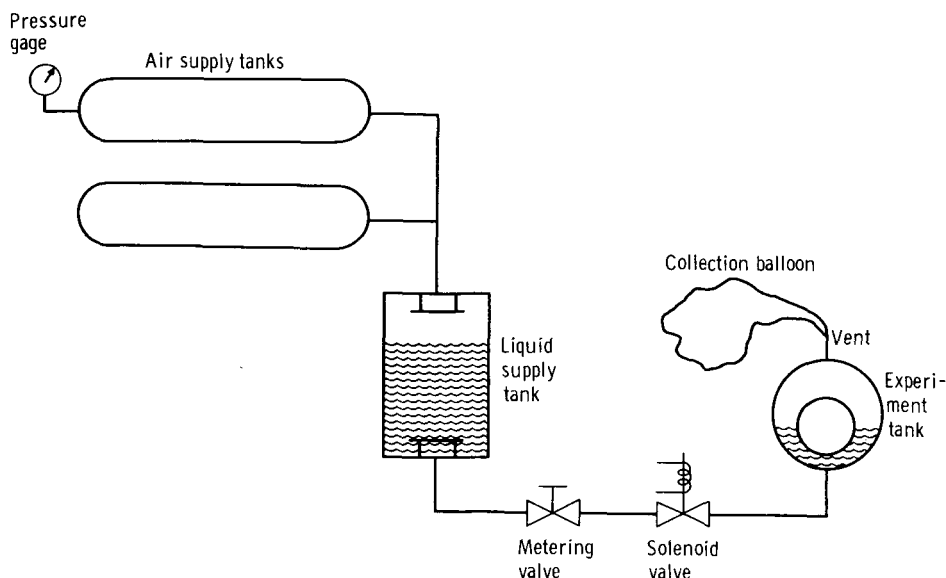


Figure 6. - Schematic diagram of pumping system.

TABLE I. - PROPERTIES OF TEST LIQUIDS

[Temperature, 20° C; pressure, 1 atm.]

Liquid	Density, g/cc	Surface tension	
		dynes/cm	N/m
Distilled water	0. 9982	72. 7	0. 0727
Ethanol	. 7890	22. 0	. 0220

## Test Liquids

Two liquids were used in the investigation. They were distilled water, which is a partially wetting liquid, with an observed contact angle greater than 70°, and 200 proof ethanol, which is a totally wetting liquid, with a contact angle of 0° on the surfaces investigated. A small amount of dye was used to improve the photography of the liquids; however, the dye had no measurable effect on the liquid properties. Values for density and surface tension are given in table I.

## Operating Procedure and Data Analysis

Preparation of the experiment involved cleaning, assembling, and filling the pumping system. Before the experiment tank was assembled, it was ultrasonically cleaned in a solution of distilled water and detergent. Distilled water was also used for rinsing.

Drying was accomplished by immersing the tank in a hot-air dryer which supplied purified air. The remaining parts of the pumping system were similarly cleaned.

After assembly of the system into the rig, liquid was added by filling the supply tank. The system was then primed to eliminate air bubbles. The initial liquid filling was established in the experiment tank and in the supply tank, and the metering valve was adjusted to obtain the desired inlet velocity.

Inlet velocity measurements were obtained in the following manner. First, the air supply tanks were pressurized. Then the shutoff solenoid valve was opened, and the flow occurred. Displacement of the liquid-vapor interface in the supply tank was measured after every test drop. The time during which flow occurred in zero gravity was recorded on 16-millimeter film. Thus, by knowing the dimensions of the liquid supply tank, the flow rate from the tank was calculated. Finally, the velocity of the liquid into the test experiment was calculated using the diameter of its inlet together with the known flow rate. Accuracy of the calibrated velocity was  $\pm 2$  centimeters per second because of limitations in reading the displacement scale. Flow was started after the static equilibrium configuration was formed and was stopped when either the tank was 90 percent full or weightlessness ended, whichever occurred first.

## RESULTS AND DISCUSSION

### Inflow Stability Criteria

In order to define the inflow characteristics of a liquid during weightlessness, criteria establishing flow stability are necessary. During inflow, the interface may be distorted to some degree, and at high velocities geysering may occur; however, by selecting a limit to the amount of interface distortion a flow stability criterion can then be defined. In this particular case, stable flow was defined as that condition where no part of the liquid reached the tank vent. Inversely, the velocity which resulted in liquid flowing out of the vent was defined as an unstable velocity. Also, as a part of this stability criteria, the incoming liquid was required to form a continuous interface between the tank wall and the baffle with no entrained vapor bubbles existing in the liquid.

### Inflow Characteristics During Weightlessness

Performance in an unbaffled spherical tank. - The results of pumping water (a partially wetting liquid) into a spherical tank are presented in figure 7, where inlet velocity is plotted against percent initial filling. In this figure, two velocities are shown for each filling; the higher velocity represents the minimum value obtained for unstable flow and

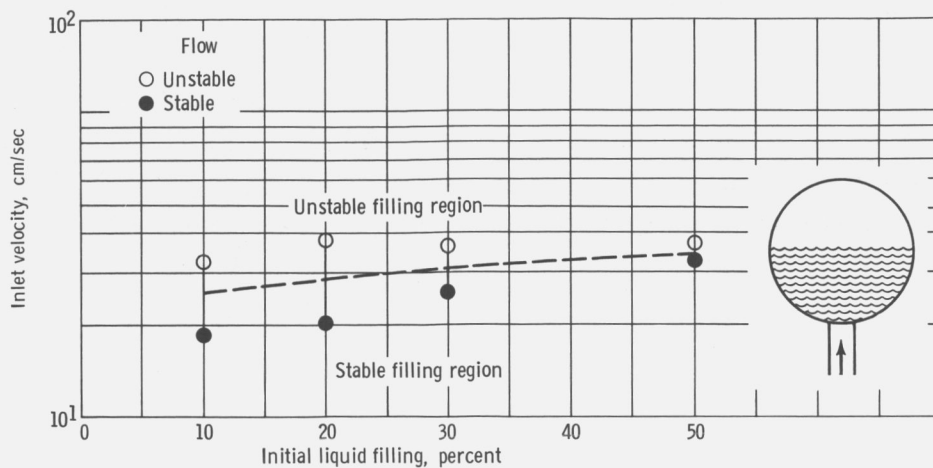
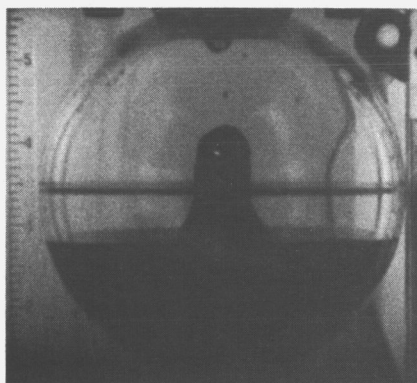
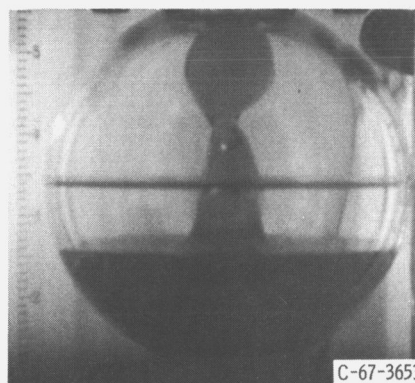


Figure 7. - Performance in weightlessness of unbaffled tank with water as test liquid.



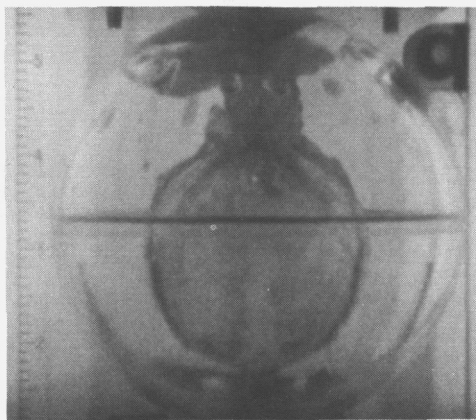
(a) Stable flow. Initial fill, 30 percent; velocity, 25.6 centimeters per second; elapsed pumping time, 0.80 second; maximum geyser height, 3.3 centimeters.



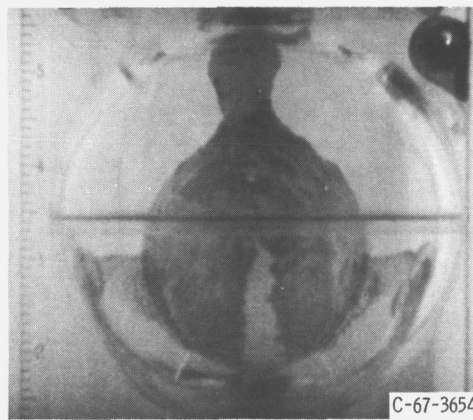
(b) Unstable flow. Initial fill, 30 percent; velocity, 35.2 centimeters per second; elapsed pumping time, 0.86 second; geyser shown hitting vent.

Figure 8. - Photographs showing flow stability in weightlessness during inflow of water to unbaffled tank.





(a) Test fluid, distilled water. Velocity, 140 centimeters per second.



(b) Test fluid, 200 proof ethanol. Velocity, 70.1 centimeters per second.

Figure 9. - Photographs depicting unstable flow in baffled tanks during weightlessness. Initial fill, zero percent; elapsed pumping time, 0.75 second; geyser has formed and reached vent position.

the lower velocity is the maximum value obtained for stable flow. A curve was drawn through the averages of these points thus approximating the critical velocity between stable and unstable flow.

The curve indicates very little or no effect of initial filling on allowable inflow velocity. In general, the inflow velocity is low, on the order of 30 centimeters per second. Typical photographs depicting inflow in both stable and unstable regions are shown in figure 8. In figure 8(a), although the interface is distorted (note axial geyser), flow is considered stable because no liquid reached the vent. While the geyser was forming, it was oscillating slightly in the vertical direction. The photograph shows the geyser at its maximum height, approximately 3.3 centimeters. Figure 8(b) illustrates unstable flow showing a geyser with liquid flowing through the vent.

The unbaffled spherical tank was tested with water only; the zero-gravity equilibrium configuration using ethanol (a totally wetting liquid) results in a totally wetted sphere and is therefore unstable in that, even with zero inlet velocity, the vent is covered with liquid.

Performance in baffled tanks. - The flow stability criteria for the baffled tanks were identical to the unbaffled sphere. Here, however, the interface configuration was considerably different because of the surface tension baffle. At the higher velocities in the unstable region and at zero percent initial filling, the liquid, due to momentum and surface tension, flowed around the baffle and geysered directly to the vent. Photographs for this unstable configuration with water and with ethanol are shown in figure 9. Note that some of the ethanol has flowed along the webs reaching the tank wall, while the webs in the water tank remained dry.

The performance of the baffled tank with water is presented in figure 10. The data establish the regions of stable and unstable flow. The effect of initial filling on inflow

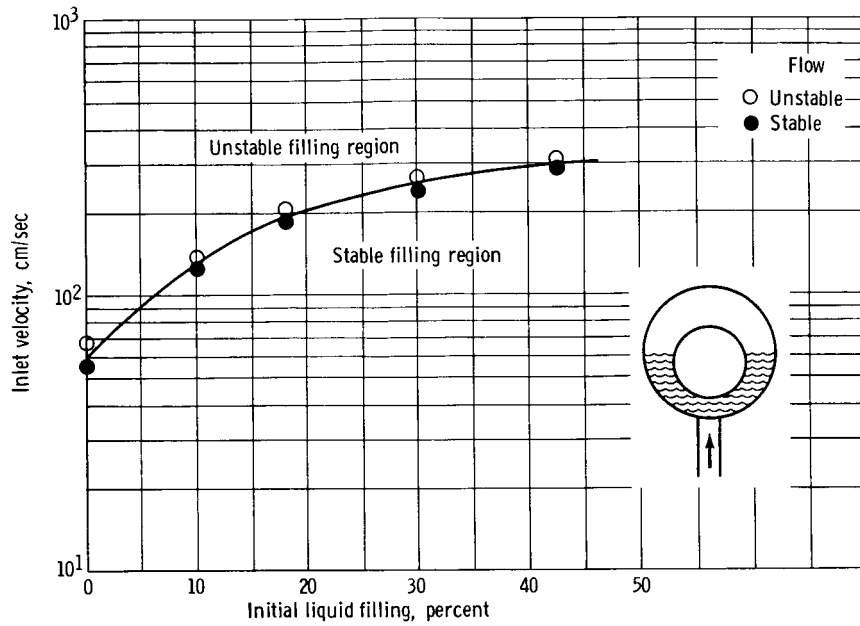


Figure 10. - Performance in weightlessness for baffled tank with water as test liquid.

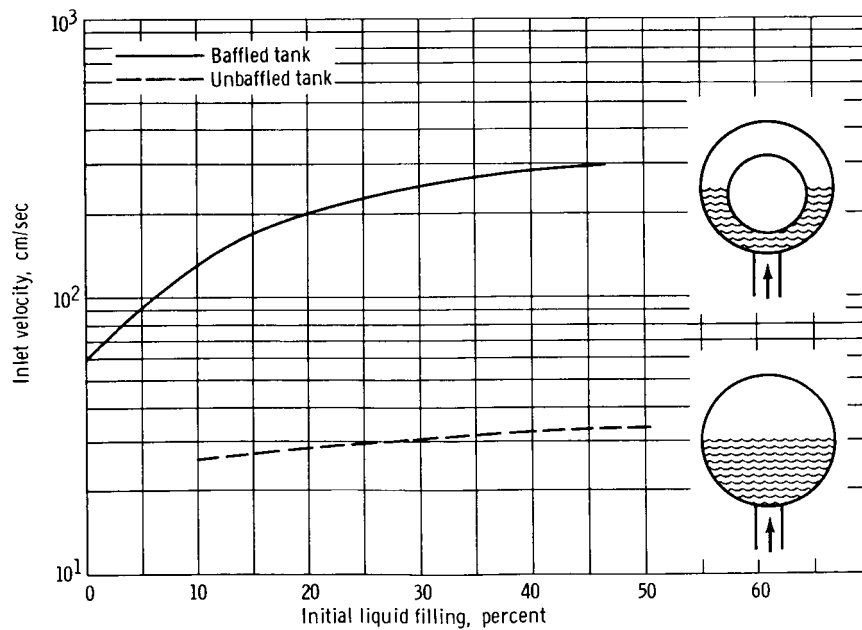
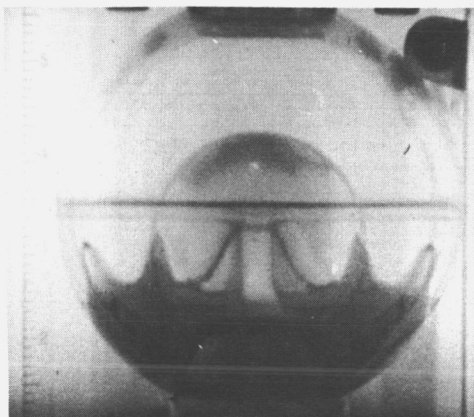
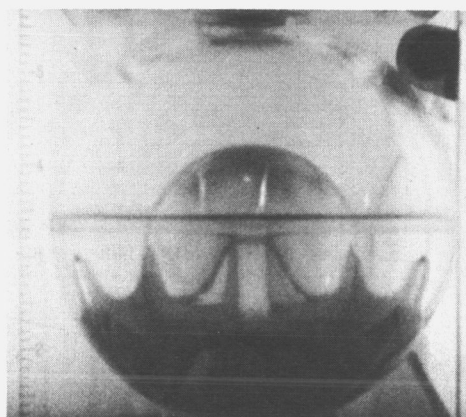


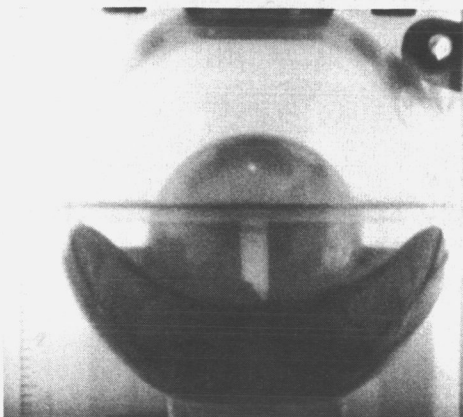
Figure 11. - Baffled tank effectiveness in weightlessness with water as test liquid.



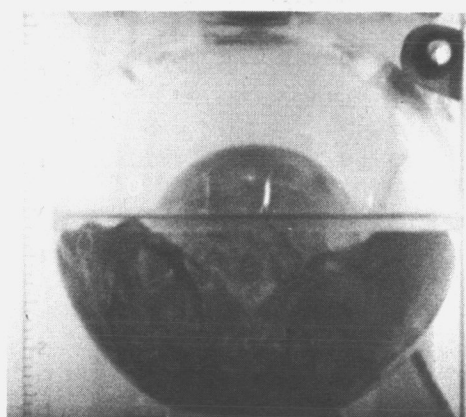
Zero gravity; time, 0 second; pumping starts.



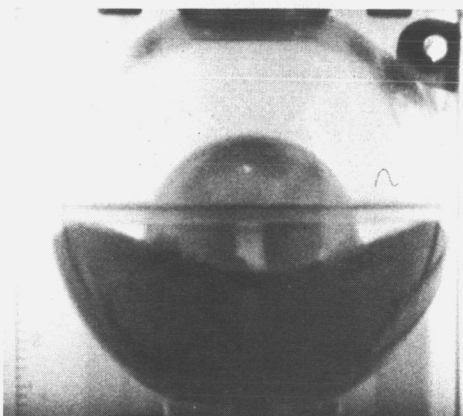
Zero gravity; time, 0 second; pumping starts.



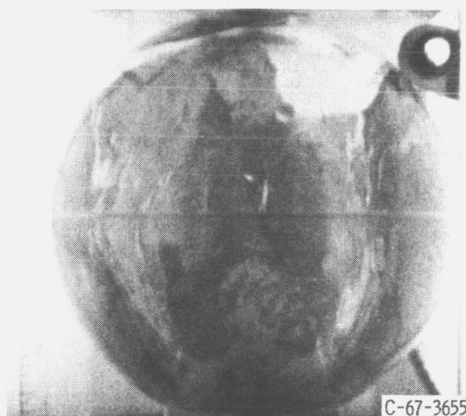
Time, 0.87 second.



Time, 0.88 second.



Time, 1.73 seconds; pumping ends.



Time, 1.76 seconds; pumping ends.

(a) Stable flow. Velocity, 66 centimeters per second.

(b) Unstable flow. Velocity, 78 centimeters per second.

Figure 12. - Filling of baffled tank with ethanol showing stable and unstable flow. Initial fill, 10 percent.

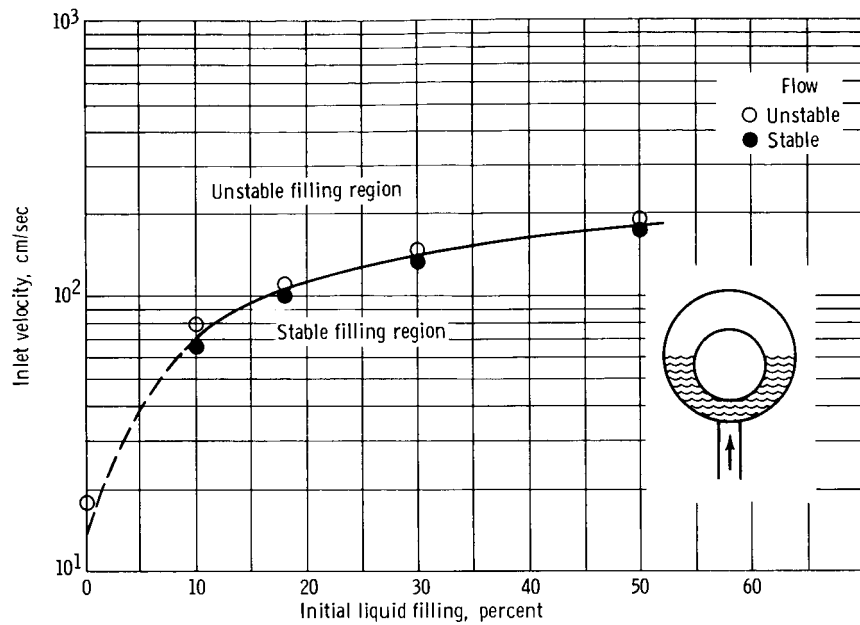


Figure 13. - Performance in weightlessness for baffled tank with ethanol as test liquid.

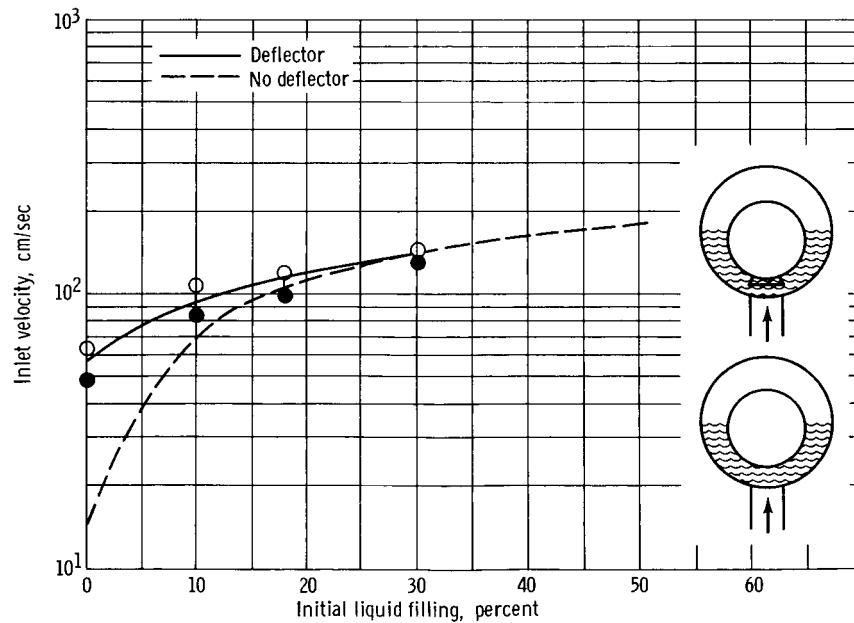
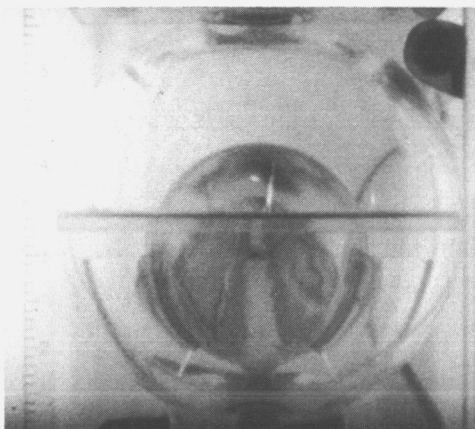
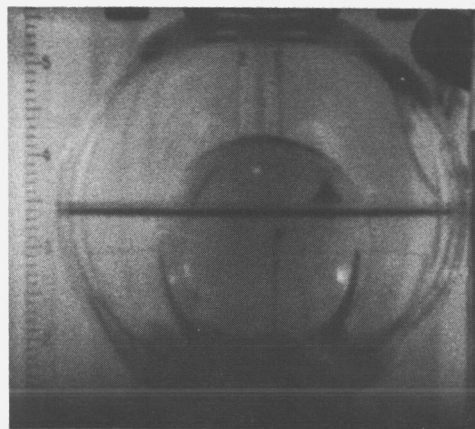


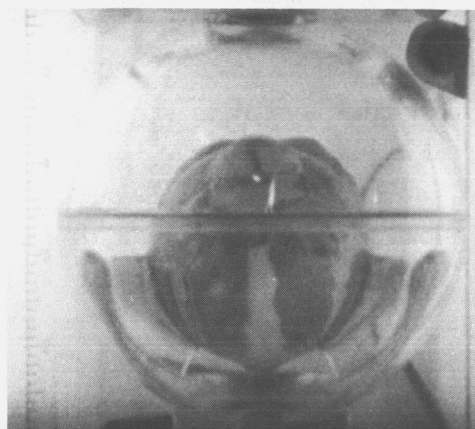
Figure 14. - Inflow deflector performance in weightlessness with ethanol as test liquid.



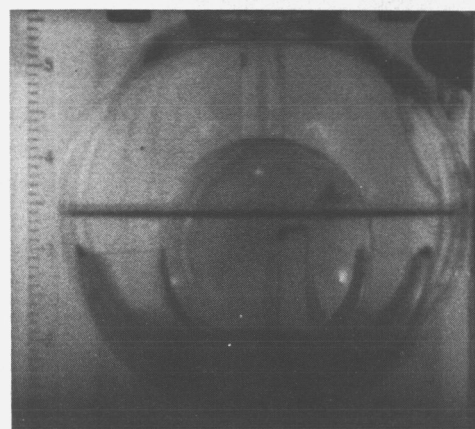
Zero gravity; time, 0.44 second; pumping has started.



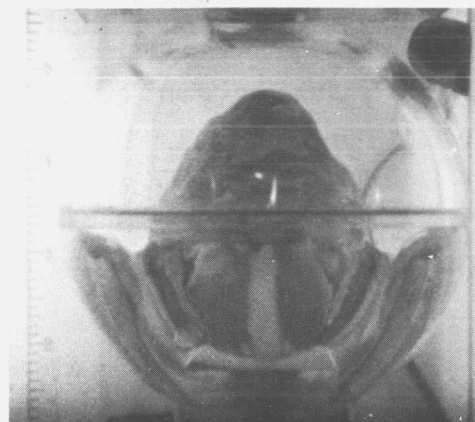
Zero gravity; time, 0.44 second; pumping has started.



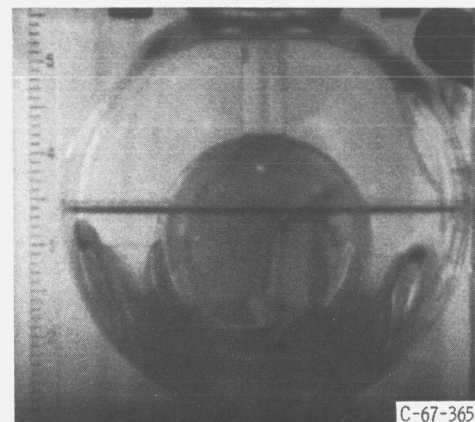
Time, 0.88 second.



Time, 0.88 second.



Time, 1.76 seconds.



Time, 1.76 seconds.

(a) No deflector. Velocity, 42 centimeters per second.

(b) Deflector. Velocity, 48 centimeters per second.

Figure 15. - Film sequence showing effect of deflector with ethanol as test fluid. Initial fill, 0 percent.

velocity is more evident here than in the unbaffled tank. Allowable velocities ranged from approximately 60 centimeters per second for the initially empty tank to 290 centimeters per second at 43.5 percent initial fill. This higher filling represented the maximum initial filling at that velocity such that the liquid did not exceed 90 percent of the tank volume during the test. The effectiveness of the baffle is clearly demonstrated in figure 11, where the velocity curves for both baffled and unbaffled tanks are compared. For the baffled tank, allowable velocities were increased 5 times at 10 percent filling and nearly 9 times at 45 percent filling.

A photographic sequence of a baffled tank being filled with ethanol is given in figure 12. Figures 12(a) and (b) show the stable and unstable flow configurations, respectively, for a given initial filling of 10 percent. The first frame in figure 12(a) gives the zero-gravity equilibrium configuration at the time pumping starts. The next frame shows the interface during inflow; it appears smooth and stable with peaked points occurring where the webs contact the tank wall. The final frame indicates that the interface remains stable with only a slight change in height in the area between the webs. In figure 12(b), the interface begins to distort in the second frame. Distortion is increased in the last frame, and liquid is going through the vent.

Performance of the baffled tank with ethanol is shown in figure 13. At 50 percent initial filling, allowable velocity was 180 centimeters per second; 10 percent initial fill allowed a velocity of 70 centimeters per second. Notice, however, for the initially empty tank a stable point was not obtained. The lowest accurate velocity obtainable with the test system was 17 centimeters per second and was in the unstable region. Therefore, the data are shown as a dashed line for fillings below 10 percent. The behavior of ethanol pumped into the initially empty tank at low velocities was apparently capillary or surface tension dominated. The liquid core entering the tank reached the baffle surface without spreading to the tank wall. Once the liquid reached the baffle, it tended to completely wet the surface including the baffle supporting webs. Although the liquid never reached the vent at low velocities, these points were unstable because a continuous liquid-vapor interface could not be formed between the tank wall and the baffle. In the case of water, a stable point was obtained at zero percent filling because the liquid was deflected off the baffle toward the tank wall and a complete interface was formed.

Performance in baffled tank with deflector. - As a result of this extremely poor performance with ethanol at low velocities, a simple inflow deflector was employed in an effort for improvement. The deflector design as described in the section APPARATUS significantly improved the filling performance as shown in figure 14. The velocity as a function of initial fill curves are presented for the baffled tank with and without the deflector. The deflector enhanced the allowable velocity greatest at zero percent fill; improvement was lessened with increasing initial fill until no noticeable effect was apparent at 30 percent filling. A photographic comparison of the deflector operation is given in figure 15. In figure 15(a) at an inlet velocity of 42 centimeters per second,

the flow configuration is unstable. In the first picture the liquid has partly wet the baffle and is beginning to wet the webs. The second frame shows the baffle completely wetted and part of the liquid has begun to wet the wall of the tank where the tank makes contact with the webs. A geyser is forming in the third frame, and the tank wall is only wetted near the contact area of the webs. The wall area between the webs is not wetted and the interface between the wall and baffle is incomplete, thus producing an unstable configuration. Note, because of reflection through the liquid on the baffle, it might appear that the deflector is in this sequence of photographs. However, this is not the case. Figure 15(b) shows the tank with the deflector and an incoming velocity of 48 centimeters per second resulting in a stable configuration.

### Effect of Wettability

The effect of wettability on stable flow with and without a surface tension baffle is summarized in figure 16. Presented in this figure are the critical velocity curves for water and ethanol. Consider first the baffled tank curves; the similarity of the shape of both curves is evident between 10 and 50 percent fillings. Distilled water, the partially wetting liquid (contact angle greater than  $70^\circ$ ), was stably pumped into the tank at approximately twice the pumping rate of ethanol, the totally wetting liquid (contact angle  $0^\circ$ ). Photographs of each liquid flowing into a baffled tank at similar velocities are given in figure 17. The water is stable while the ethanol reaches the vent and is unstable. Referring again to figure 16, the deflector is shown to increase the critical veloc-

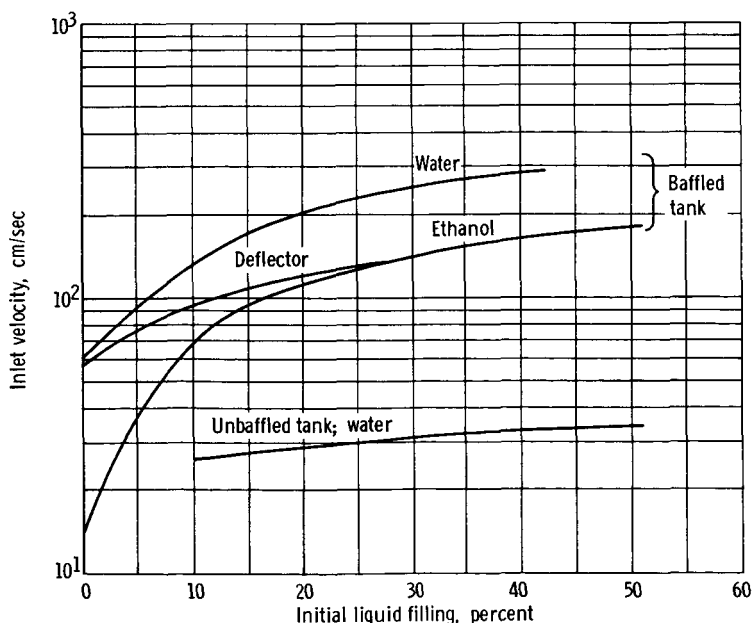
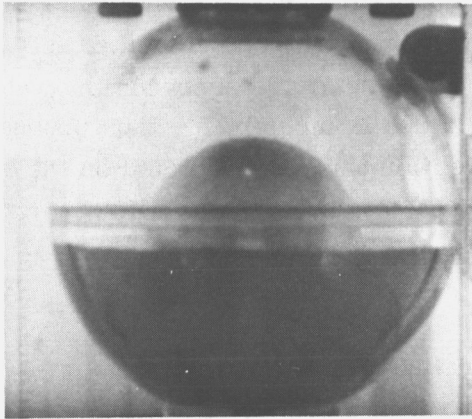
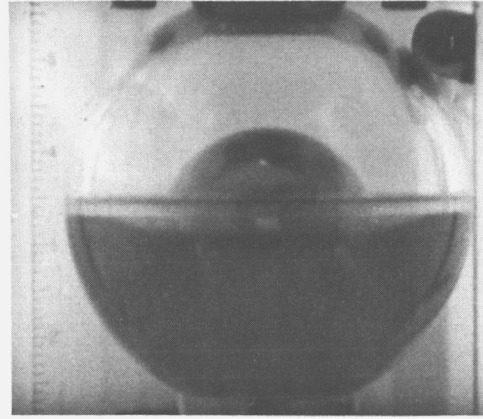


Figure 16. - Effect of wettability on stable inflow with and without surface tension baffle.

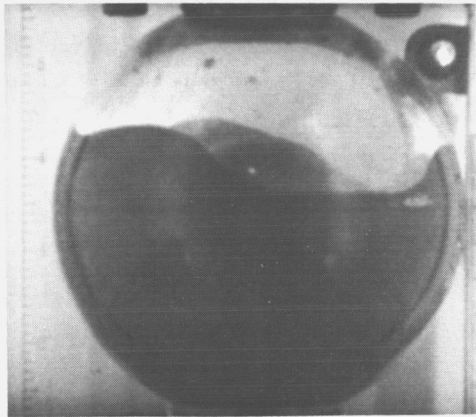




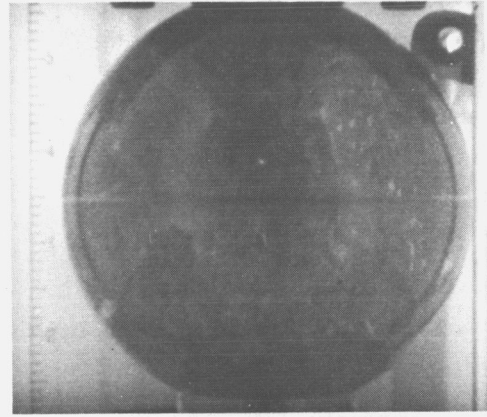
Zero gravity; time, 0 second; pumping starts.



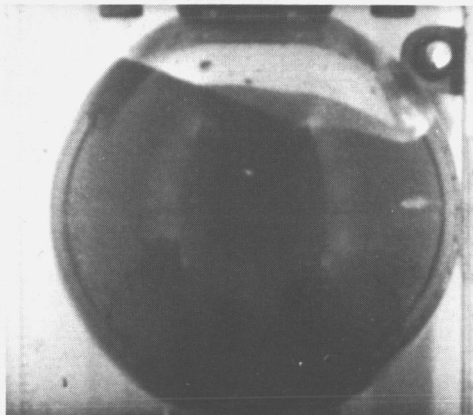
Zero gravity; time, 0 second; pumping starts.



Time, 0.88 second.



Time, 0.87 second.



Time, 1.76 seconds; pumping ends.

(a) Water.



Time, 1.77 seconds; pumping ends.

(b) Ethanol.

Figure 17. - Film sequence of baffled tank being filled with water and ethanol at similar velocities of 226 centimeters per second. Initial fill, 30 percent.



ity of ethanol to a value very close to that of water (without a deflector) in an initially empty tank. A final comparison of the curves indicates, in general, that the baffled tank permits higher filling rates than the unbaffled tank regardless of the wettability of the fluid.

## SUMMARY OF RESULTS

An investigation of liquid flow into a baffled spherical tank during weightlessness was conducted. Two liquids were tested, distilled water and ethanol. Based on the criteria chosen for stability in zero gravity and for a 10-centimeter-diameter tank with a 6-centimeter-diameter baffle, the following conclusions can be stated:

1. Liquids can be pumped into a spherical tank in zero gravity over a range of velocities which maintain the liquid-vapor interface in a stable orientation; the maximum value of these velocities increases with increasing initial liquid filling in the tank.

2. The baffled sphere permitted higher inflow velocities than the unbaffled sphere; with water the velocity was nearly five times greater at 10 percent initial filling and as much as nine times greater at 45 percent filling.

3. For initial fillings greater than zero with baffled tanks, allowable inflow velocities for water were approximately twice those obtained for ethanol. A stable inflow velocity for ethanol, at zero percent initial filling, was not obtained.

4. Modifying the surface tension baffle with a deflector was effective in considerably improving the allowable inflow velocities of ethanol at low initial fillings; for an initially empty tank, the rate of filling was nearly equivalent to that obtained for water without a deflector.

Lewis Research Center,  
National Aeronautics and Space Administration,  
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